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ORIGINAL ARTICLE

Underground Geodiversity of Italian Show Caves: an Overview

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Abstract

About a fifth of the Italian territory is characterised by the presence of soluble rocks, consisting mainly of limestone and dolostone but also of marble and evaporite rocks (gypsum). More than 50,000 natural caves are currently known in this country, a number that is constantly increasing thanks to speleological exploration. Less than 1% of these caves are equipped for visits, and only 64 can be defined as real show (tourist) caves. In the latter, it is necessary to buy an entrance ticket, visits take place only accompanied by a guide, and the underground trail is equipped with paths, walkways and, generally, lighting systems. The Italian show caves expose a great geodiversity and biodiversity, often accompanied by a considerable historical and/or archaeological interest. The underground geodiversity of Italian show caves is related to the variety of lithologies characterising this territory and to the geomorphological and geodynamic processes that have been active during different geological periods. Important scientific research has taken place in many of these caves, and several of these fragile environments are monitored continuously to verify their environmental conditions.

Keywords Tourism · Commercial caves · Karst · Scientific research · Geomorphology

Introduction

Caves are environments characterised by significant heterogeneity in terms of both geological and biological features which are referred to as geodiversity and biodiversity of the subterranean ecosystem. The evaluation of the geodiversity of caves is based on physical elements that are an expression of the genetic and evolutionary processes that shape these environments (Stepišnik and Trenchovska 2018; Pontes et al. 2019). They are represented by abiotic characters such as size (length, passage size, depth, etc.), diversity and distribution of speleothems, internal meso- and micromorphological characteristics, types and composition of sediments, and other geological elements. Cave biodiversity, on the other hand, is an index of karst ecosystem health and is measured on the basis of the population and variety (understood as the number of species) of living organisms, their degree of adaptation, and the habitat suitability (Christman and Culver 2001; Balestra et al. 2021; Wynne et al. 2021). Among these animal species, *Homo sapiens* should also be included. Indeed, although marginally participating in the dynamics of cave dwellings, our species has left traces of its presence in these environments since prehistoric times and continues to be a frequent visitor. Since caves are conservative environments, some of these traces have been preserved over time, providing important information about our ancestors. However, sometimes they also carry the signs of the negative impact of human activities. Nevertheless, the biotic and abiotic characteristics of caves, together with the historical ones, are the cornerstones of their great scientific value. Thanks to their exceptional characteristics, some caves can be commercially exploited, and in the meantime, they can be used to fruitfully disseminate knowledge to the general public.

Currently, international policy states the necessity to protect the natural capital, the world's stock of natural resources, which includes geology, hydrology, soil, air, vegetation, and all living organisms and provides essential goods

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and services (EEA 2018). Natural capital also includes cave geodiversity (Gray 2019; Kuhn et al. 2022). On the basis of the five classification groups proposed by Gray (2018) for abiotic environmental services, show caves offer several important ecosystem services: (1) they support subterranean habitats and participate in geomorphological processes, (2) they regulate carbon and hydrogeological cycles, and (3) they often supply large quantities of high-quality freshwater (provisioning services). Besides the ecosystem service groups listed above, show caves also include non-tangible elements such as (4) cultural (geotourism) and (5) knowledge services (education, environmental monitoring, employment, and the ability to reconstruct past environmental and climatic conditions of the Earth).

Caves, together with canyons and volcanoes, are among the most visited geological features in the world. A recent investigation (Chiarini et al. 2022) has estimated over 1200 show caves in the world, attracting more than 70 million people every year. Over 95% of these world's show caves are hosted in soluble rocks and can be defined as karst caves, whereas the rest can open in volcanic rocks, intrusive lithologies such as granites and quartz sandstones.

In Italy, about 21% of the territory can be considered 'karst' that is made up of rocks that can be dissolved by water which, penetrating inside fractures, can excavate real underground tunnel networks called 'karst systems'. Based on the data extrapolated from the map of Italian karst areas created by the Italian Speleological Society in collaboration with the Geological Service of Italy (ISPRA) (Sivelli and De Waele 2013), these rocks are mostly represented by limestones and dolostones, which together make up about 93% of the entire Italian karst surface, followed by evaporitic rocks (about 6%, mostly composed of gypsum) and marbles (about 0.6%) (Fig. 1). All the Italian administrative divisions have a certain percentage of karst territory, ranging from 0.6% in the Emilia-Romagna region to 45% in Puglia. It follows that karst phenomena are an integral part of the geological processes that occur throughout the national territory. Caves can potentially form in any type of rock and through a great variety of processes (e.g. volcanic activity, wind and ice action, tectonic deformation…). However, karst dissolution is the most common and frequent speleogenetic process (Ford and Williams 2007; De Waele and Gutiérrez 2022). The presence of a relatively large karst territory means that numerous caves have formed in Italy (it is estimated that there are over 50,000 caves) in all its administrative divisions. It is noteworthy to mention that the region with the smallest karst surface (0.6%), Emilia-Romagna, has at least 750 caves currently recorded within its scattered karst areas (most of them are carved in gypsum).

In Italy, based on our knowledge, there are currently at least 500 caves open to some extent to the general public, corresponding to about 1% of the total number of natural caves currently known in the country. These are generally easy-to-access caves, known to the local inhabitants, and visitable without speleological equipment. Often, due to their accessibility (if not properly closed with a gate), they have been vandalised and show heavy signs of frequentation by cavers and occasional visitors. In addition to these caves, there are several others adapted along vertical sections for more demanding visits, which require the use of speleological equipment and the presence of qualified cave guides. This more adventurous type of tourism is gaining increasing interest. Stairs and fixed supports have been installed in several of these caves to facilitate progression, but the underground environments are not equipped with lighting systems, and access is not always regulated. Payment for the visit is therefore made directly to the accompanying person (often a speleological guide) and includes the rental of equipment, insurance, and the guide service. It should be remembered that the situation of the caves that can be visited changes from year to year, with some of these adventurous caves passing to the organised tourist management (installation of infrastructure for visits), and others being abandoned, or new caves being equipped and used for speleological tours. Unfortunately, this last phenomenon, if not properly controlled, in some cases is leading to deterioration of some underground environments.

In this work with 'tourist caves' (show or commercial cave, in technical English) we intend those corresponding to the following characteristics (Chiarini et al. 2022): (1) it is necessary to buy an entrance ticket (possibly only certified speleologists can enter without paying); (2) one must be accompanied by a guide, who provides explanations and oversees the safety of visitors; (3) the cave is equipped with a system of paths, stairs, and walkways (or boats if the cave is totally flooded, for example the Grotta Azzurra on Capri Island) to facilitate visits; (4) the underground environment is generally equipped with a lighting system (also operated from the boat in the case of a completely flooded cave). According to these points, which are based on the definition of 'show cave' provided by the Italian Show Caves Association (AGTI), there are at least 64 show caves in Italy, distributed in 16 administrative divisions (Tables 1 and 2). Regions such as Valle d'Aosta, Trentino-Alto Adige, Molise, and Sicily are the only ones that do not have any show caves, despite the presence of karst territory and many explored wild caves.

Although Italy is not the nation with the largest number of show caves in the world (for example, France has over 100, Spain more than 70, while the US and China in 2020 had about 150 and 75, respectively) (Chiarini et al. 2022), for most people these caves represent the first contact with the underground world and, consequently, with caving. On one hand, the adaptations needed to open a show cave can be very invasive and substantial, and the presence of many visitors,

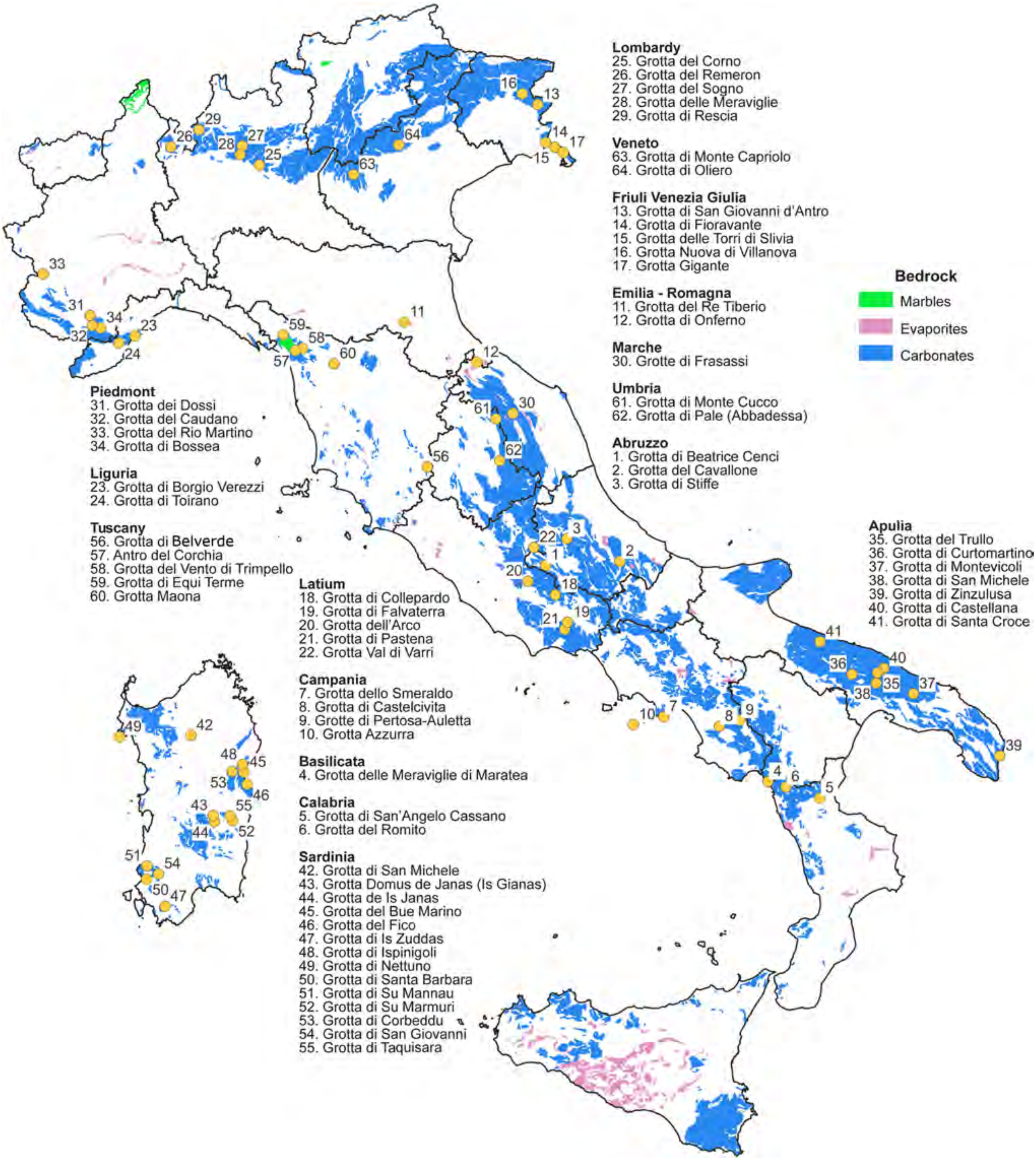

Fig. 1 Map of karst rocks in Italy (modified from Sivelli and De Waele 2013). Yellow dots indicate the location of the Italian show caves in each administrative region. The numbers refer to the list in Table 2

as well as the lighting systems, introduce a certain degree of perturbation (Piano et al. 2022) and pollution to the underground environment, such as microplastics on cave walls, speleothems, and sediments (Balestra and Bellopede 2022). On the other hand, being closed and watched over, these caves are protected from accidental damage and vandalism due to occasional visits, and cave managers themselves have every interest in safeguarding the asset they manage.

Table 1 Percentage of karst territory and number of show caves in each Italian region. The data were calculated on the basis of the Italian karst areas map (Sivelli and De Waele 2013) and of the vector files of the Italian regions' borders provided by Istat (https://www.istat.it/it/Archivio/222527)

Administrative division	ID	Regional surface (10^3 km^2)	% of karst territory	N. show caves
Valle d'Aosta	VA	3.3	4.6	0
Piedmont	PM	25.4	5.7	4
Liguria	LG	5.4	11.3	2
Lombardy	LO	23.9	15.8	5
Trentino-Alto Adige	TAA	13.6	31.1	0
Veneto	VE	18.3	22.8	2
Friuli-Venezia Giulia	FVG	7.9	44.5	5
Emilia-Romagna	EM	22.4	0.6	2
Tuscany	TO	23.0	6.4	5
Umbria	UM	8.5	30.2	2
Marche	MA	9.4	32.9	1
Latium	LT	17.2	29.2	5
Abruzzo	AB	10.8	40.0	3
Campania	CP	13.6	30.9	4
Molise	MO	17.2	25.8	0
Apulia	PU	19.4	44.6	7
Basilicata	BA	10.0	16.3	1
Calabria	CL	15.1	11.3	2
Sicily	SI	25.7	26.6	0
Sardinia	SA	24.1	11.4	14

After a historical overview, this paper discusses the geodiversity of the 64 Italian show caves in terms of geological features (cave morphologies and deposits) and speleogenesis. This showcase on the underground world represents an important scientific outcome that can be disseminated in show caves, becoming a tool for raising global awareness on the importance of karst and its multiple resources, and to highlight the need to enforce environmental protection of these fragile ecosystems (Sanna and De Waele 2010; Piano et al. 2022). At the same time, the valorization of Italian karst geodiversity can contribute to the competitiveness of the production system of the regional economies and the rural areas (Garofano 2018).

Historical Overview

Hidden beneath the Earth's surface, shrouded in total darkness, caves have attracted humans since ancient times. Used primarily as shelters, especially in the parts near the entrances, they soon became the object of real explorations, as evidenced by the footprints in the Grotta della Bàsura in Toirano (Liguria) (see Table 2 and Fig. 1 for the cave location from here on) (Citton et al. 2017), or the cave paintings of the Porto Badisco cave in Apulia (Graziosi 1980). Written reports on sporadic visits to some caves in Italy date back to Roman times, but often, the geographical references are not detailed enough to understand exactly which places were visited. The Grotta Azzurra (Blue Grotto) (Campania) was used as a Roman 'nymphaeum' (sanctuary of the nymphs), as indicated by the marble statues found on the seabed at the site (Squarciapino 1969), and modifications, probably of Roman age in the inner, dry parts of the cave (Kyrle 1947) (Fig. 2a and b).

In some cases, caves were used as hiding places for more or less legitimate activities. For example, it appears that in the Middle Ages there was a flourishing business of counterfeiters inside the Grotta del Re Tiberio (Fig. 2c) (Gelichi 1996). During the Second World War, many caves were used as a refuge (for example, Re Tiberio and Onferno in Emilia-Romagna, and Pertosa-Auletta in Campania) or even as the headquarters of German armed troops, as in the case of Pastena Cave (Latium). In many examples, ancient wall writings (graffiti) testify the reasons and periods of frequentation in some cave, such as those dating back to the fifteenth century, in the Sanctuary Cave of Santa Lucia Superiore (Toirano, Liguria). Here, there are many signatures and names left by pilgrims who entered the deep darkness of this rectilinear tunnel, a sort of *ante litteram* 'explorers' (Columbu et al. 2021).

In all the sites mentioned above, we are not yet dealing with real cave 'tourist visits', in the sense that there was no economic exploitation yet, but rather with a frequentation linked to the use of an environment whose characteristics were suitable for the needs of the moment. It is from the seventeenth century that visits to the most famous Italian caves begin to increase. This phenomenon of cave visits, widespread throughout Europe, acts as a forerunner for real underground tourism, which, at first, mainly involved the aristocratic world (only rich people could afford such luxury). Writers, queens, kings, and princesses began to show interest in the underworld and to ask to be accompanied in that mysterious and enchanted world. It seems that Queen Christina of Sweden, for example, visited the Cave of Pale (or Grotta dell'Abbadessa, Foligno, Umbria) in 1652 (Baldanza et al. 2014). A little later, the date '1666' engraved in the so-called 'Stone of Ancient Names' at the entrance of the Grotta del Cavallone (Abruzzo) is supposed to be evidence of an anonymous visit to this not-easy-to-access place, opening high up on the cliffs of the Majella Mountains (Fig. 2d) (Piccone 2016).

The oldest signatures in the Balma di Rio Martino (Piedmont) date back to the mid-seventeenth century (Magrì 2006). In the early 18th century, the Buca di Equi (Tuscany) was described by Vallisneri (1726), while in a

Table 2 Main geological characteristics of the 64 Italian show caves

N.	Name	AGTI	Region	Protection	Lithology	Rock age	Vistors/year (2019)	Length (m)	Pattern	Speleogenesis
1	Grotta di Beatrice Cenci	N	AB	SIC IT 7110091	Limestones	Miocene	3000	200	L-R	Active river
2	Grotta del Cavallone	Y	AB	Majella National Park	Limestones - marly limestones	Paleocene - Oligocene	10,000	2500	L	Sulfuric
3	Grotte di Stiffe	Y	AB	Sirente Velino Natural Regional Park	Limestones - calcarenites	Cretaceous	30,000	6500	L	Active river
4	Grotte delle Meraviglie di Maratea	N	BA	SIC IT9210155	Limestones - dolostone	Cretaceous	20,000	700	R	Vadose flow
5	Grotta di Sant'Angelo	N	CL	None	Dolostones	Triassic	5000	2500	M	Sulfuric
6	Grotte del Romito	N	CL	Pollino National Park—Fiume Lao Natural Reserve	Limestones	Jurassic	10,000	35	A	Erosion
7	Grotta dello Smeraldo	N	CP	Monti Lattari Regional Park	Limestones	Cretaceous	100,000	45	R	Coastal mixing
8	Grotta di Castelcivita	Y	CP	Cilento & Vallo di Daiano National Park—Riserva naturale Foce Sele Tanagro	Limestones	Cretaceous	20,000	4800	L	Active river
9	Grotta di Pertosa Auletta	Y	CP	Riserva naturale Foce Sele—Tanagro	Limestones	Jurassic	80,000	3000	L	Active river
10	Grotta Azzurra	N	CP	SIC IT9030038	Limestones	Jurassic	50,000	300	L-R	Coastal mixing
11	Grotta del Re Tiberio	N	ER	SIC IT4070011	Gypsum	Miocene	3000	4000	L	ancient river
12	Grotta di Onferno	Y	ER	Riserva naturale orientata di Onferno	Gypsum	Miocene	10,000	800	L	Active river
13	Grotta di San Giovanni d'Antro	N	FVG	None	Limestones (flysch)	Eocene	3000	4000	L	Ancient river
14	Grotta Fioravante	N	FVG	SIC IT3341002	Limestones	Cretaceous	3000	45	R	Vadose flow
15	Grotta delle Torri di Slivia	Y	FVG	None	Limestones	Cretaceous	3000	550	L	Vadose flow
16	Grotta Nuova di Villanova	Y	FVG	None	Limestones (flysch)	Eocene	20,000	8000	L	Active river
17	Grotta Gigante	Y	FVG	None	Limestones	Cretaceous	100,000	700	R	Vadose flow
18	Grotta di Collepardo	N	LT	SIC IT6050008—Monti Simbruini	Limestones	Cretaceous	10,000	200	R	Vadose flow
19	Grotte di Falvaterra[1]	N	LT	Monumento Naturale Grotte di Falvaterra e Rio Opaco	Limestones	Cretaceous	3000	5000	L	Active river
20	Grotta dell' Arco	N	LT	SIC IT6030035	Limestones	Cretaceous	3000	1000	L	Active river

Table 2 (continued)

N.	Name	AGTI	Region	Protection	Lithology	Rock age	Vistors/year (2019)	Length (m)	Pattern	Speleogenesis
21	Grotta di Pastena[1]	N	LT	SIC IT6050022—Grotta di Pastena	Limestones	Cretaceous	50,000	5000	L	Active river
22	Grotta di Val de' Varri	Y	LT	SIC IT6020022	Limestones	Cretaceous	20,000	1800	L	Active river
23	Grotta di Borgio Verezzi	Y	LG	None	Dolomitic limestones	Triassic	30,000	1600	M	Coastal mixing
24	Grotte di Toirano (Basura – Santa Lucia)	Y	LG	SIC IT1324011-Monte Ravinet—Rocca Barbena	Dolomitic limestones	Triassic	200,000	1700	L-M	Mixing CO_2
25	Buco del Corno	N	LB	None	Limestones	Jurassic	3000	670	L	Vadose flow
26	Grotta del Remeron	Y	LB	Campo dei Fiori Regional Park	Limestones	Jurassic	3000	2000	L	Phreatic rise
27	Grotte del Sogno	N	LB	None	Dolostones	Triassic	3000	200	L	Vadose flow
28	Grotta delle Merav-iglie	N	LB	None	Limestones	Triassic	3000	320	L	Vadose flow
29	Grotta di Rescia	N	LB	None	Travertines	Quaternary	20,000	90	M	Deposition
30	Grotte di Frasassi	Y	MA	Gola della Rossa e di Frasassi Natural Regional Park	Limestones	Jurassic	400,000	35,000	M	Sulfuric
31	Grotta dei Dossi	N	PM	None	Metalimestones - dolostones	Triassic	10,000	910	M	Vadose flow
32	Grotta del Caudano inferiore	Y	PM	None	Metalimestones - dolostones	Triassic	10,000	3000	L	Active river
33	Grotta (Balma) di Rio Martino	N	PM	SIC IT1160037	Metadolostones	Jurassic	10,000	3200	L	Active river
34	Grotta di Bossea	Y	PM	SIC IT1160026	Metalimestones - dolostones	Triassic	30,000	3000	L	Active river
35	Grotta del Trullo	Y	PU	None	Limestones	Cretaceous	10,000	100	R	Mixing CO_2
36	Grotta di Curtomar-tino	Y	PU	None	Limestones	Cretaceous	3000	50	R	Vadose flow
37	Grotta di Montevicoli	N	PU	None	Limestones	Cretaceous	25,000	100	R	Vadose flow
38	Grotta di San Michele Arcangelo	N	PU	None	Limestone breccia	Cretaceous	1000	50	R	Vadose flow
39	Grotta di Zinzulusa	N	PU	Costa-Otranto—Santa Maria di Leuca e Bosco di Tricase Natural Regional Park	Limestones	Oligocene	100,000	300	L-M	Coastal mixing
40	Grotte di Castellana	Y	PU	SIC IT9120001	Limestones	Cretaceous	300,000	3400	L	Mixing CO_2
41	Grotta di Santa Croce	N	PU	None	Limestones	Cretaceous	5000	130	L	vadose flow

Table 2 (continued)

N.	Name	AGTI	Region	Protection	Lithology	Rock age	Vistors/year (2019)	Length (m)	Pattern	Speleogenesis
42	Grotta di San Michele	N	SA	None	Metalimestones	Devonian	3000	50	M	Mixing CO_2
43	Grotta de Is Gianas (Domus de Janas)	N	SA	None	Dolostones	Jurassic	3000	310	L	Ancient river
44	Grotta de Is Janas	N	SA	None	Dolostones	Jurassic	10,000	240	L	Ancient river
45	Grotta del Bue Marino	N	SA	Golfo di Orosei e del Gennargentu National Park	Limestones	Jurassic	80,000	72,000	L-M	Active river coastal mixing
46	Grotta del Fico	Y	SA	Golfo di Orosei e del Gennargentu National Park	Limestones	Jurassic	20,000	2000	L-M	Coastal mixing
47	Grotta di Is Zuddas	Y	SA	None	Metadolostones	Cambrian	50,000	1350	M	Mixing CO_2
48	Grotta di Ispinigoli	N	SA	None	Limestones	Jurassic	40,000	10,000	L-R	active river
49	Grotte di Nettuno	N	SA	Porto Conte Natural Regional Park	Limestones	Cretaceous	200,000	3000	L-M	Coastal mixing
50	Grotta di Santa Barbara	N	SA	SIC ITB040029	Metadolostones	Cambrian	20,000	110	R	Thermal
51	Grotta di Su Mannau	Y	SA	None	Dolostones	Cambrian	20,000	8200	L	Active river
52	Grotta di Su Marmuri	Y	SA	None	Dolostones	Jurassic	20,000	860	L	Ancient river
53	Grotta Corbeddu	N	SA	SIC ITB022212—Golfo di Orosei e del Gennargentu National Park	Limestones	Jurassic	10,000	140	L	Ancient river
54	Grotta di San Gio-vanni	N	SA	Regional Natural Monument	Metadolostones	Cambrian	30,000	5000	L	Active river
55	Grotta Taquisara	N	SA	SIC ITB021103	Dolostones	Jurassic	1000	1070	L	Ancient river
56	Grotte di Belverde[2]	N	TO	Archeological Park	Travertines	Quaternary	5000	300	M	Deposition
57	Antro del Corchia	Y	TO	Alpi Apuane Natural Regional Park	Dolostones - Marbles	Triassic - Jurassic	10,000	65,000	L-M	Active river
58	Grotta del Vento di Trimpello	Y	TO	Alpi Apuane Natural Regional Park	Dolostones	Triassic	70,000	4600	L-M	Active river
59	Grotte di Equi Terme	N	TO	Alpi Apuane Natural Regional Park	Dolomitic marbles	Jurassic	20,000	700	L-M	Active river
60	Grotta Maona	N	TO	None	Limestones	Jurassic	5000	140	M	Thermal
61	Grotta di Monte Cucco	N	UM	Monte Cucco Regional Park	Limestones	Jurassic	10,000	40,000	M	Sulfuric
62	Grotte dell' Abbadessa di Pale	N	UM	SIC IT5210038	Limestones	Jurassic	3000	100	L	Vadose flow
63	Grotta di Monte Capriolo	N	VE	None	Limestones	Jurassic	30,000	240	L-R	Vadose flow

Table 2 (continued)

N.	Name	AGTI	Region	Protection	Lithology	Rock age	Vistors/year (2019)	Length (m)	Pattern	Speleogenesis
64	Grotta di Oliero	N	VE	SIC IT3220007	Dolostones	Triassic	5000	100	L-M	Active river
Total number of caves		**64**				**Total visitors**	**2,387,000**			

[1]Pastena and Falvaterra are the sink and resurgence of the same karst system, respectively

[2]Belverde caves are several small alcoves and caves, the longest of which is 300 m long

The number in the first column (*N*) corresponds to the cave number on the map in Fig. 1. The third column reports the affiliation (*Y* = yes) or not (*N* = no) to the Italian Show Cave Association (AGTI)

Regions: *AB* Abruzzo, *BA* Basilicata, *CL* Calabria, *CP* Campania, *ER* Emilia-Romagna, *FVG* Friuli Venezia Giulia, *LB* Lombardy, *LG* Liguria, *LT* Latium, *MA* Marche, *PM* Piedmont, *PU* Apulia, *SA* Sardinia, *TO* Tuscany, *UM* Umbria, *VE* Veneto

Patterns: *L* linear, *R* room, *A* alcove, *M* maze

letter sent in 1793 by Monsignor Del Duca to King Ferdinand IV, a detailed description of the Zinzulusa Cave in Apulia (Del Duca 1957) is reported. The Grotta di Nettuno in Sardinia was described in 1805 by Giovanni Andrea Massala, son of a noble family from Alghero, in a 45-page booklet (Massala 1805; Mucedda and Pala 1990) (Fig. 2e).

In those times, however, cave tourism was organised only occasionally, making use of local guides and adventurous transport means (on the back of donkeys, or using motorized vehicles), often upon payment of porters, guides, drivers, interpreters, and various labourers, but still caves were not regularly open to the public, charging prices for entrance 'tickets'.

The first 'ticket' for a tourist visit to a cave date back to 1633 at Jama Vilenica (Cave of Corgnale), in Slovenia, when Count Benvenuto Petazzi introduced an entrance tax to cover the costs of the nearby church of Lokev (Cigna 2019). Thanks to its strategic position, just over 10 km from the important harbour of Trieste and at short distance from the road that connected Vienna to the Adriatic, this cave was the most visited in Europe at that time. Towards the end of the eighteenth century, with the construction of the new road and railway (mid-nineteenth century), but above all with the opening of the nearby Postojna Cave (Slovenia), Corgnale lost most of its appeal, but still today, it is visitable from April to September, or upon demand.

In Postojna, the Adelsberg Cave (Postojnska Jama) was opened to public in 1824 but in the 'passage of ancient signatures', numerous writings dating back to the sixteenth century (the oldest could date back to 1413) testify to sporadic visits starting from that period (Kempe 2003; Cigna 2019). Also, on this site in 1872, the little train that still takes visitors inside the cave (driven by charcoal first, but fortunately riding on electricity now) came into operation, and in 1884 Postojnska was among the first in Europe to be equipped with an electrical lighting system (after Sloupsko-Šošùvské Jeskyně in Czechoslovakia, now Czech Republic, and Kraushöhle in Austria, respectively in 1881 and 1883).

The great success obtained in these caves gave an important impetus to the opening of the first show caves also in neighbouring Italy. The first was the Grotta Parolini in Veneto (known as Grotta di Oliero), one of the springs of the Asiago plateau, feeding Brenta River, near Vicenza (Fig. 2f). The cave, discovered in 1822, was opened for visits in 1832 at the instigation of the naturalist Alberto Parolini (Parolini 1858). After the use of explosives in order to widen the entrance, which was too low on the surface of the water to allow a safe visit, tourists were transported by boats, upon purchase of an entrance ticket. The Bossea Cave (Piedmont) was probably explored as early as 1816 by Matteo Velia, as some writings seem to indicate (https://grottadelvento.wordpress.com/2015/08/07/141/), but the first documented exploration dates back to 1850, when Domenico Mora, a local mountaineer, reached the shores of the underground Ernestina's Lake, almost 500

Fig. 2 Show cave history. **a** and **b** Two old postcards of Grotta Azzurra, on the North coast of Capri Island, probably one of the most depicted show caves of Italy (collection F. Anelli Library Bologna). **c** Picture of the entrance of the Re Tiberio Cave, northern Apennines, before its tourist adaptation (photo Piero Lucci). Note the excavated niches on the left, showing the cave to have been used since prehistoric times. **d** Picture of the 'Stone of the Autographs' at the entrance of Cavallone Cave, Majella Mts. The date '1666' shows this remote cave entrance to have been visited for over 350 years (photo Tonino Piccone). **e** Seaward view of the entrance of Grotta di Nettuno, Sardinia. Lithography of Day & Son (for Victoria, Queen of England in 1824) in William Henry Smyth's book '*Sketch of the present state of the island of Sardinia*', John Murray ed., London (collection F. Anelli Library Bologna). **f** Drawing of the entrance of Parolini Cave (Oliero, along the Brenta River) by Pietro Chevalier, 1828 (collection F. Anelli Library Bologna)

m into the mountain. The initial part of Bossea was opened to the public in the summer of 1874, thus becoming the second show cave in Italy, even if the installation of the electrical lighting system was completed only more than 70 years later, in 1948 (Peano and Fisanotti 1994).

In the same region and period (1878), the Balma di Rio Martino cave was equipped with walkways, railings, and steps carved into the rock, although the first adaptations were made in 1854 to facilitate visits by Prince Umberto and the Duke of Aosta (Magrì 2006). This cave is listed among the true show caves, mainly because of historical reasons, even though illumination has never been put in place. In the nearby Grotta dei Dossi, discovered in 1797 by a hunter, the electrical lighting system was installed in the summer of 1893, when it was opened to the public, almost a century after its first exploration (Salino 1877). Due to the low number of visitors, this cave was closed in 1914, followed by its abandonment, and since then subject to vandalism, causing intentional damage to the speleothems. The cave was reopened only in 1966, and nowadays only attracts a small number of visitors per year.

At the beginning of the twentieth century, the Grotta di Santa Lucia Superiore (Toirano, Liguria) was equipped with acetylene lamps to allow pilgrims to visit it. The Grotta Gigante (Briššćkova Jama) near Trieste (Friuli Venezia Giulia), probably discovered by Lindner in 1839, and then re-explored by Schmidl in 1851, was opened after 3 years of works in July 1908, although electric lighting only arrived in 1957 (Forti 1989). In southern Italy, the first show caves were those of Pertosa-Auletta and Castelcivita in the Alburni Mts., close to Salerno (Campania) (Battaglia 1929; Rodriguez 1974). Both caves have been made accessible since the beginning of the 1930s, although the second was equipped professionally only in 1968 (Aloia et al. 2014). In Apulia, the Trullo caves (Putignano) and those of Castellana were opened, respectively, in the years 1931–1935 and in 1939, only a few years after their discovery and exploration (Stefanelli 1934; Anelli 1938).

In the 1970s, the number of show caves along the Italian peninsula had reached fifty: in Verole Bozzello (1970) 44 show caves are listed, in Badini (1974) five more are mentioned. Forti and Cigna (1989) roughly estimated that at least twenty of the show caves open in Italy in the late 1980s attracted at least 25,000 visitors a year, and some largely exceeded 100,000 visitors. Currently, a number totalling at least 2.5 million tourists are estimated for all Italian show caves (Chiarini et al. 2022) (Table 2). In the meantime, the number of caves open to the public continued to increase, albeit slowly: Floris (1995) reported eleven in Sardinia (compared to five reported by Verole Bozzello 1970) to which are added those opened in recent decades, such as Fico Cave in 2003 (Maddanu and Porcu 2017) and Taquisara Cave a few years later. The Antro del Corchia (Tuscany) was adapted for visits in 2001 (Amorfini and Bartelletti 2004), as was the Grotta di Val di Varri in the province of Rieti (Latium), accessible after a prolonged series of works in 2003 (Forti and Mecchia 2000). The Torri di Slivia Cave (Friuli Venezia Giulia) was adapted to tourism by Romano Ambroso (a passionate caver who dug the sediments of the entrance in the early 1960s), starting from the mid-1960s, with the opening of the current stairway entrance and internal paths. Unfortunately, following his death (in 1976) the show cave did not take off, and the site was instead gradually abandoned and devastated due to the ease of access (Toffanin 2016). After long years of legal struggles and disputes between owners, it was finally opened to the public in 2012, supporting a small private business (Federazione Speleologica Triestina 1996). The caves of Falvaterra (Latium) are among the last to have been equipped for public visits in 2014 (Carè and Russo 2000).

The Grotta di San Giovanni in Sardinia deserves a separate paragraph: this 860-m long natural tunnel was used, probably since prehistoric times, as a shortcut connecting the mountains to the plain, and traversed by people on foot, horse (or donkey)-pulled carts, cars, and trucks. Although this cave was probably one of the most visited in Sardinia, its tourist management started only very recently, after finally being cleaned up and equipped with the most modern lighting systems in 2020 (Naseddu et al. 2022).

Geodiversity

The term 'geodiversity' includes the whole variability of natural geological and geomorphological features on Earth, including the abiotic phenomena that shape the landscape (Gray 2018). Karst geodiversity is a peculiar type of the geological resources as its landscape is characterised by a three-dimensional space that includes surface and underground features. Caves are portions of the subterranean world that extend under the Earth's surface whose environmental heterogeneity depends on the different lithologies in which they develop, the processes involved in their shaping, and the time during which they form. Of the 64 Italian show caves considered in this work, most are developed in limestone (37 caves, corresponding to approximately 58% of the total), while of the remaining 27, 11 are carved in dolostones (17%), 8 in metalimestones or metadolostones (13%), and 2 (3%) in each of travertines, gypsum, marbles, and calcareous flysch (conglomerates). The age of the rocks hosting these caves ranges between the Cambrian (dolostones and metadolostones in Sardinia) and the Quaternary (travertines in Lombardy and Tuscany): 41 caves (64%) are housed in rocks from the Jurassic and Cretaceous periods, while 11 (17%) in the Triassic lithologies. Almost two thirds of all Italian show caves are therefore found in Mesozoic rocks, only five in Palaeozoic rocks (4 caves in the Cambrian and 1 in the Devonian, all in Sardinia), while the remainder were formed in tertiary rocks (7 caves) and in Quaternary travertines (2 caves). The great geodiversity of Italian show caves not only lies in the age and petrography of the host rocks but also in their great variety of morphologies, their clastic sediments and secondary deposits (i.e. speleothems and minerals), and the speleogenetic processes that led to their formation. These topics are discussed in the following subchapters.

Cave Morphologies

The large geodiversity of subterranean environments derives mainly from dissolution of the bedrock by water, which represents one of the dominant geomorphic processes in karst. Its contribution in shaping cave morphologies is a direct function of hydrological dynamics that control underground geometric patterns and geomorphological features. The 64 Italian caves open to the public are variable in size and morphology, going from the very shallow and small alcoves of the Grotta del Romito, in Calabria (Martini 2002) or some of the Belverde caves (Tuscany) to extensive cave systems of several tens of kilometres long, such as the Bue Marino Cave in Sardinia, which is part of the Codula Ilune Cave System, around 72-km long (Buschettu et al. 2016), the Corchia Cave System (Tuscany), over 64-km long (Piccini 2019), and Frasassi and Monte Cucco Cave Systems (Marche), both over 35-km long (Guzzetti 1987; Bertolani and Cigna 1994; Galdenzi and Jones 2017; Galdenzi and Menichetti 2017). In these very large cave systems, only a short portion of their underground network is open to the public, as shown in Fig. 3.

Generally, most caves are not deep, or at least the parts open to visits are not. However, the Corchia cave system has an altitudinal difference between the highest and lowest branches of 1210 m, and the Monte Cucco cave system reaches almost 920 m in depth.

Cave patterns also have a great variety (Fig. 4), with most systems elongated linearly or/and sinuously along a horizontal main branch (43 caves, corresponding to 67% of all caves). Although having a general linear plan, nine of these also have maze sectors, and four have sinuous or/and angular branches starting from a large room. Ten cave systems (over 15%) have a maze pattern, the same number (10) are more or less single rooms, and one is an alcove with a short inner

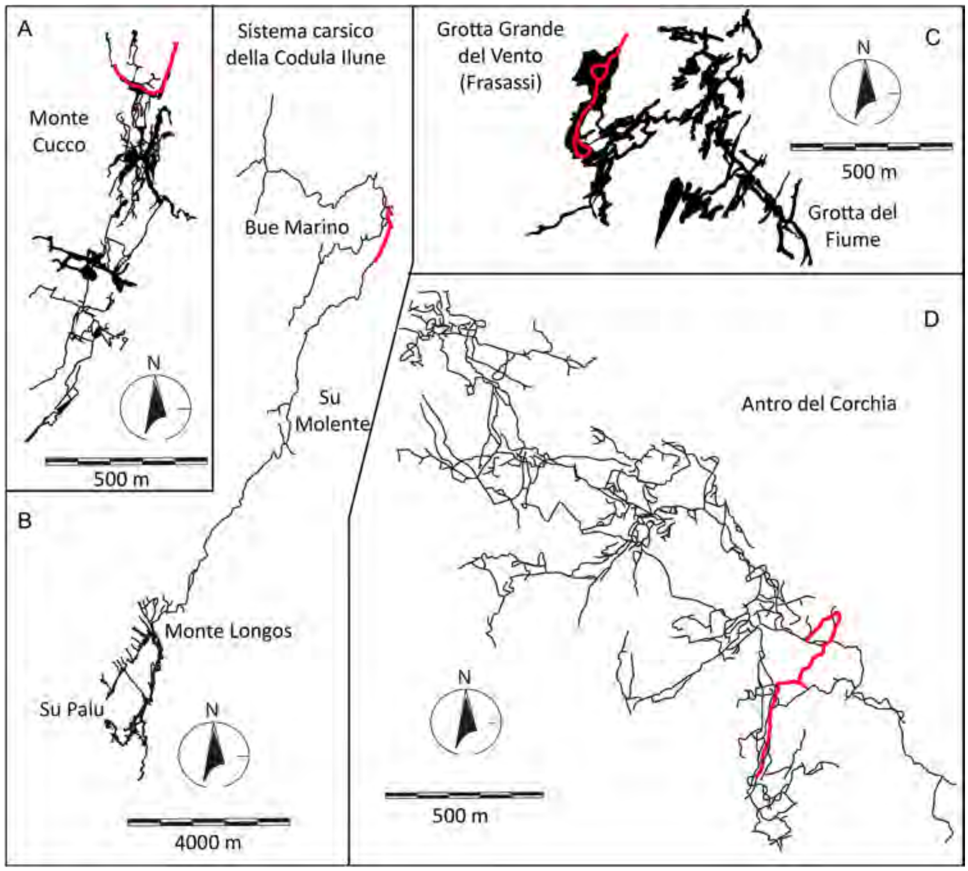

Fig. 3 Large (over 30-km long) cave systems from Italy with a small part open to public (shown as red traces). **A** Monte Cucco Cave, Umbria. **B** Codula Ilune Cave System, Sardinia. **C** Frasassi Cave System, Marche. **D** Corchia Cave, Tuscany

extension. Regarding their position, out of the 64 caves, most are located in mountainous areas (43, corresponding to 67% of all caves), thirteen open up on low-lying plateaus or hilly landscapes (20%), and eight (12.5%) are very close to (or in contact with) the present coastline (and sea).

Also, cave entrances come in many shapes and sizes (supplementary table). Some show caves have huge natural entrances, carved by past or still active rivers such as Grotta di San Giovanni (De Waele and Pisano 1998) (Fig. 5a) and Su Marmuri (De Waele et al. 2012) in Sardinia and Pastena in Latium (Ferri Ricchi 2001). Other caves have large portals due to slope retreat, such as Cavallone Cave in Abruzzo (Burri 1978; D'Angeli et al. 2019a; Pisani et al. 2021), or to collapse of the ceiling of a large underground void, e.g. Castellana Cave in Apulia (Pagano et al. 2020) (Fig. 5b).

The Grotta Gigante, near Trieste (Friuli Venezia Giulia), despite the sheer size of its central room, has only a few occasional minor natural accesses (Forti and Zay 2007), and also the Abisso Ancona chamber in Frassasi Cave (Marche) has only a small natural entrance (Sturba 2017). Many show caves originally had rather narrow accesses, which needed artificial widening to make the visits easier: examples are Rio Martino in Piedmont (Magrì 2006), Is Zuddas (Caddeo et al. 2008, 2015) and Taquisara in Sardinia (De Waele et al. 2012), Grotta del Vento in Tuscany (Piccini et al. 2003), Bàsura Cave (Toirano, Liguria) (Columbu et al. 2021), and Borgio Verezzi (or Valdemino) cave in the same region (Fig. 5d). Some caves were opened accidentally by excavation works (Trullo Cave in Apulia, Anelli 1938, which entrance is now hosted in a reconstructed typical country house, or 'trullo', see Fig. 5c), by quarrying, such as San Michele Cave in Sardinia (Mucedda and Grafitti 1981), or mining (Santa Barbara Cave in Sardinia, Pagliara et al. 2010).

Whereas some caves required few works to be made accessible to visitors, being composed of large and well-connected underground passages (e.g. Su Marmuri in Sardinia Fig. 6a) or single rooms with flat floors (e.g. Santa Barbara Cave in Sardinia, Fig. 6b), in other circumstances, artificial passages had to be dug to avoid entrance shafts, to connect adjacent chambers or to by-pass dangerous and/or submerged parts of the cave (e.g. Toirano Cave in Liguria, Fig. 6c) (Gruppo Speleologico Cycnus and Delegazione Speleologica Ligure 2001).

Where large lakes were encountered, anchored footbridges had to be installed (e.g. Pastena Cave, Latium), and wide vertical shafts were overcome by suspending winding staircases, as for example in Su Mannau Cave in Sardinia (Fig. 6d and e), or building and carving stairs and steps on steeply inclined surfaces, as for example in Grotta del Vento, Tuscany (Fig. 7b).

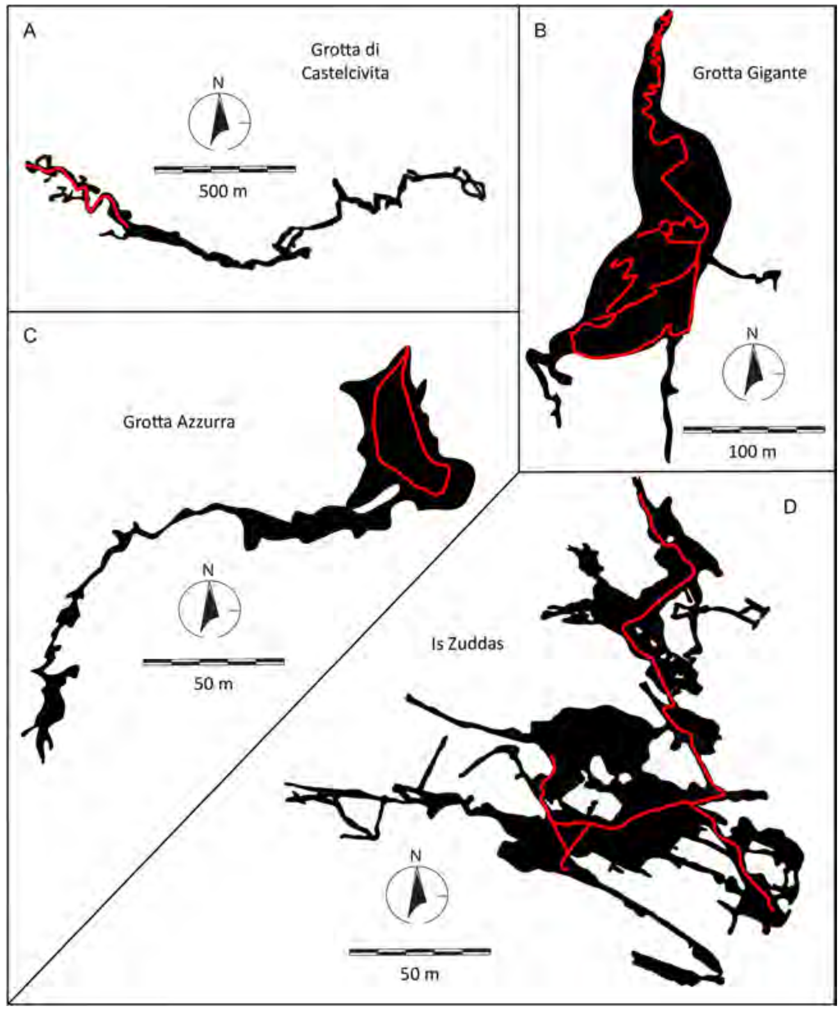

Fig. 4 Cave patterns of some Italian show caves. **A** The elongated (river) passage of Castelcivita Cave, Campania. **B** The giant room of Gigante Cave, near Trieste (Friuli-Venezia Giulia). **C** The large coastal room with the elongated passages in Azzurra Cave, Capri (Campania). **D** The maze network of Is Zuddas Cave in southwest Sardinia. The red lines show the portions of the caves open to visitors

Some of the caves have attractive morphologies due to the action of fast flowing waters (supplementary table): canyons and fluvial passages with walls decorated with hundreds of scallops can be seen in Corchia Cave (Piccini 2011) (Fig. 7a) and Grotta del Vento (Piccini et al. 2003) (Fig. 7b) both in Tuscany, in Stiffe Cave (De Dominicis 1963), in the active river caves of Latium, in some of the Piedmont caves (e.g. Caudano and Rio Martino), and in Bus del Remeron in Lombardy (Cavaleri et al. 1985). In several of these caves, the vadose passages give way to some sections with interesting phreatic morphologies, including rounded tubes and mixed vadose-phreatic shapes such as keyhole passages. Some caves are composed of large underground voids, in the form of elongated passages and chambers (e.g. Bossea Cave in Piedmont, Fig. 7c) (Antonellini et al. 2019), or isolated bell-shaped voids (e.g. Grotta Gigante in Friuli Venezia Giulia, Fig. 7d) (Forti and Zay 2007), sometimes connected to an intricate maze network (e.g. Monte Cucco in Umbria) (Galdenzi and Menichetti 2017). Most caves end in sumps, on rock falls or infillings of different types (clastic sediments or flowstones), or just become too narrow to be explorable.

In several caves, the ceilings and walls are sculptured with cupolas, in areas close to past or present fluvial activity (e.g. Grotta del Vento in Tuscany (Piccini et al. 2003); supplementary table), but also far away from any possible fluvial action (e.g. the 'Tempio' area in Castelcivita Cave in Campania, Fig. 7e). In some caves, the cupolas are accompanied with smaller morphologies such as megacusps (wavy roofs generated by condensation–corrosion phenomena), bubble trails (sinuous paths carved on overhanging walls related to rising fluids moving upward) (Fig. 7f), and rising wall channels, all indicative of rising air (or water) flows (e.g. Cavallone Cave in Abruzzo, D'Angeli et al. 2019a).

Some caves locally show spongework morphology, typical of mixing corrosion dissolution, such as Zinzulusa Cave in Apulia and Borgio Verezzi Cave in Liguria, or sulphuric acid speleogenesis, for example in Frasassi Cave (Marche), Monte Cucco in Umbria, or Sant'Angelo Cave in Calabria (Galdenzi and Maruoka 2019). The latter also shows very nice horizontal corrosion notches (indicating former water table levels in this sulphuric acid setting), similar to the coastal ones, related to the fresh-salt water mixing corrosion

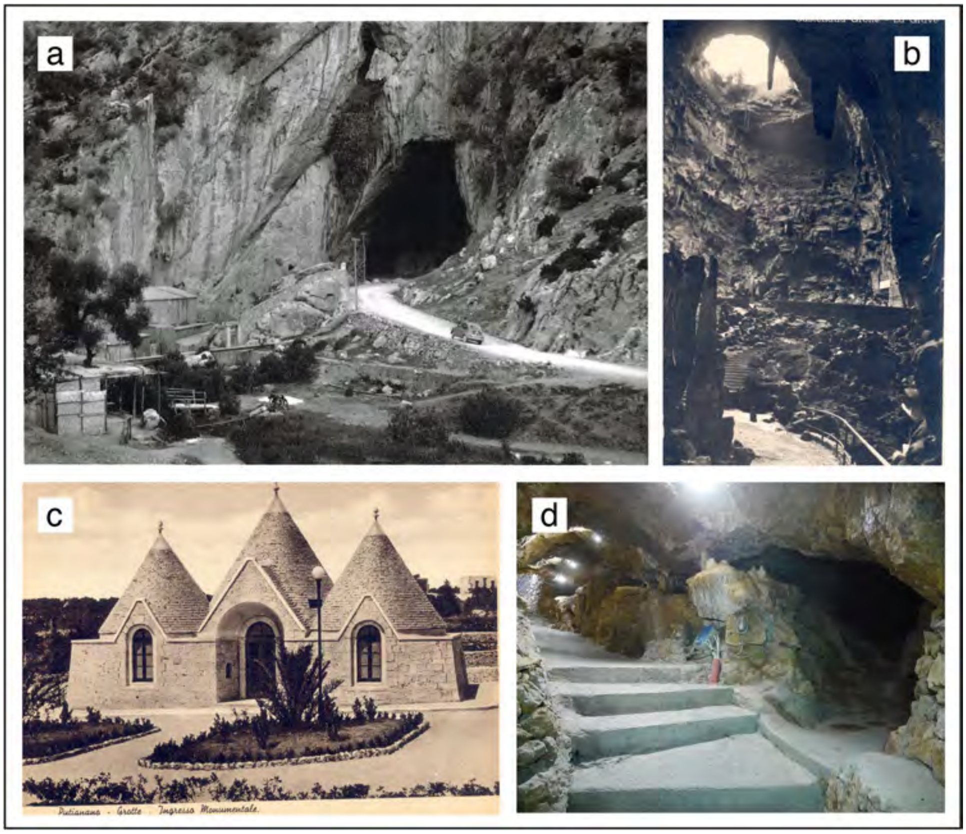

Fig. 5 Cave entrances. **a** An old picture (1950s) of the southern entrance of San Giovanni Cave in Sardinia (picture courtesy of Speleo Club Domusnovas). This river-carved passage was used until the 1990s as an over 800-m long natural road tunnel that enabled travellers to cross the mountains from the mine buildings located North to the village of Domusnovas South. **b** The natural collapse shaft (the 'Grave') of the Castellana Cave in Apulia (postcard of the collection F. Anelli Library Bologna). This is the only natural entrance to the show cave, now made accessible via an elevator and an artificial tunnel. **c** The Grotta del Trullo cave entrance (near Putignano, in Apulia), found accidentally during excavation works, has been covered with a traditional building ('trullo') hosting the museum and the ticket offices (postcard of the collection F. Anelli Library Bologna). **d** An inward view of the natural (right) and artificial passages (left) in Borgio Verezzi (Valdemino) Cave, Liguria. After its exploration through some narrow openings, an artificial tunnel was built to allow easy access to visitors (photo Bartolomeo Vigna).

dissolution active close to sea level, seen in Zinzulusa Cave in Apulia (Talà et al. 2021), or in Bue Marino (Andreucci et al. 2017) and Fico Cave (D'Angeli et al. 2015), both in Sardinia. In Bue Marino Cave the MIS5e sea-level highstand is also evidenced by the upper limit of the Lithophaga borings (Fig. 7g). Notches linked to fluvial processes at different heights are also seen in both gypsum caves in Emilia-Romagna, where these landforms are associated with antigravitative (paragenetic) ceiling pendants and interpreted as related to phases of sedimentation which obstruct the lower part of the cave conduits with consequent upward dissolution (Columbu et al. 2015).

Finally, as a curiosity, we mention the Grotta di San Giovanni near Domusnovas (Sardinia), which consists of a large tunnel passing the entire mountain (crossed seasonally by the Rio Sa Duchessa stream) completely traversable by cars (miners during the last century used this natural passageway, with donkey-pulled carts, later replaced with trucks, to transport the Pb-Zn ore from the mines upstream (North) to the processing plants in the Cixerri plain (South). It is the longest natural road tunnel that runs through a cave in the world (860-m long), and surprisingly, no parts of the cave had to be enlarged to allow vehicles (trucks) to pass (De Waele and Pisano 1998).

Cave Deposits

Once the cave voids were carved by a variety of possible processes, they were slowly infilled with both physical and chemical sediments. The sedimentary record in caves is particularly prone to be preserved over relatively long timeframes. Thus, these underground repositories often host valuable palaeontological, archaeological, and palaeoenvironmental archives. Several Italian show caves are important archaeological sites, and some are mainly open to public for their cultural heritage (e.g. Romito Cave in Calabria (Martini and Lo Vetro 2018), Fioravante in Friuli Venezia

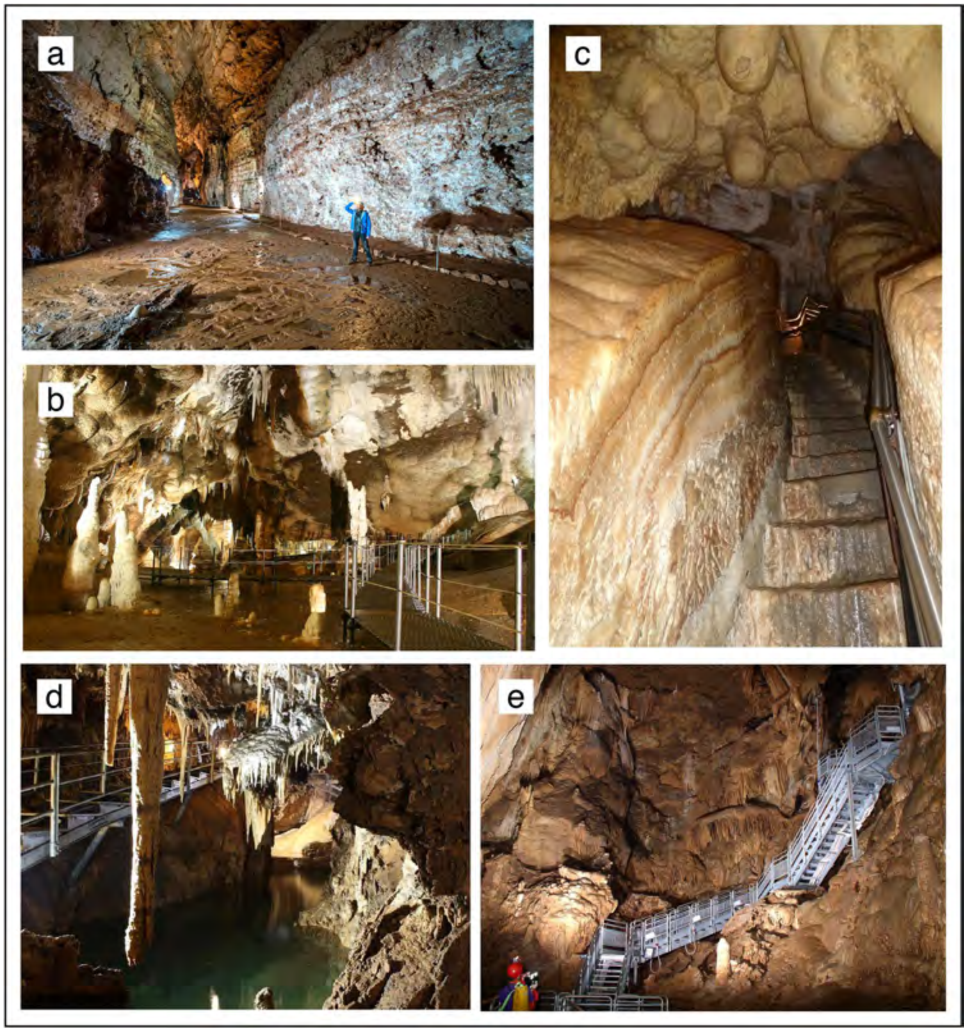

Fig. 6 Cave infrastructures. **a** The large and flat passage with rimstone dams on the floor in Su Marmuri Cave, Sardinia (photo Vittorio Crobu). Note the walkway on the right. **b** Walkways in the Santa Barbara Cave, Sardinia (photo Roberto Sarritzu). **c** Stairs excavated in massive flowstones in Bàsura Cave, near Toirano, Liguria (photo Philippe Audra). **d** and **e** Steel walkways allowing visitors to cross a lake, and to descend and climb a vertical shaft in Su Mannau Cave, Sardinia (photos Gruppo Grotte Fluminese-Su Mannau).

Giulia (Cannarella 1979), Re Tiberio in Emilia Romagna (Miari et al. 2013), the Corbeddu Cave in Sardinia (Martini 1992) (Fig. 8a), the travertine caves of Belverde in Tuscany (De Marco et al. 2021)), and the three Apulian caves Curtomartino (Iacovino et al. 2002), Monte Vicoli (Laddomada and Leporale 2004), and Santa Croce (Mallegni et al. 1987). Other caves, besides having a strong archaeological appeal, are also worth visiting from a naturalistic point of view, being finely decorated with speleothems. Toirano in Liguria (Citton et al. 2017) and Castelcivita and Pertosa-Auletta caves in Campania (Aloia et al. 2014) are the best examples. In some cases, malleable sediment sculptures similar to a field of pyramids and pinnacles (e.g. Grotta del Vento, Tuscany, Fig. 8f) can also be worth observing, delivering a welcome substitute to the otherwise much more beautiful speleothem shapes and colours.

Cave deposits can be used to date the voids they fill (or at least, they give a minimum age to them) applying U/Th and U/Pb methods for dating speleothems, using palaeontological and sedimentological indices, or carrying out cosmogenic burial dating. The latter analyses were carried out only in a few show caves. In Madonna di Frasassi Cave (Marche), fluvial sands yielded a burial age of 0.75 ± 0.26 Ma (Cyr and Granger 2008). In Genna 'e Ua Cave, Sardinia, located at the same altitude as Taquisara show cave and only 500 m away, quartz pebbles indicated a burial age of 2.74 ± 0.47 Ma (De Waele et al. 2012). In the highest level of the Toirano cave (Colombo cave, Liguria) sands gave a burial age of around 1.8 Ma (Columbu et al. 2021). Volcanic ashes of the Campanian Ignimbrite (39.85 ± 0.14 ka, related to the Phlegrean Field mega-eruption) were found sealing an archaeological deposit containing both *Neanderthal* and *Homo sapiens* artefacts in the entrance area of Castelcivita Cave in Campania (Gambassini 1997; Giaccio et al. 2008).

The aeolian sands in the entrance areas of Bue Marino Cave in Sardinia (Fig. 8b) have been dated with a particular optically stimulated luminescence (OSL) protocol on K-feldspar grains, using signals from infrared stimulated luminescence (IRSL) preceded by an initial low-temperature IR (post-IR $IRSL_{290}$ method), and comparing the

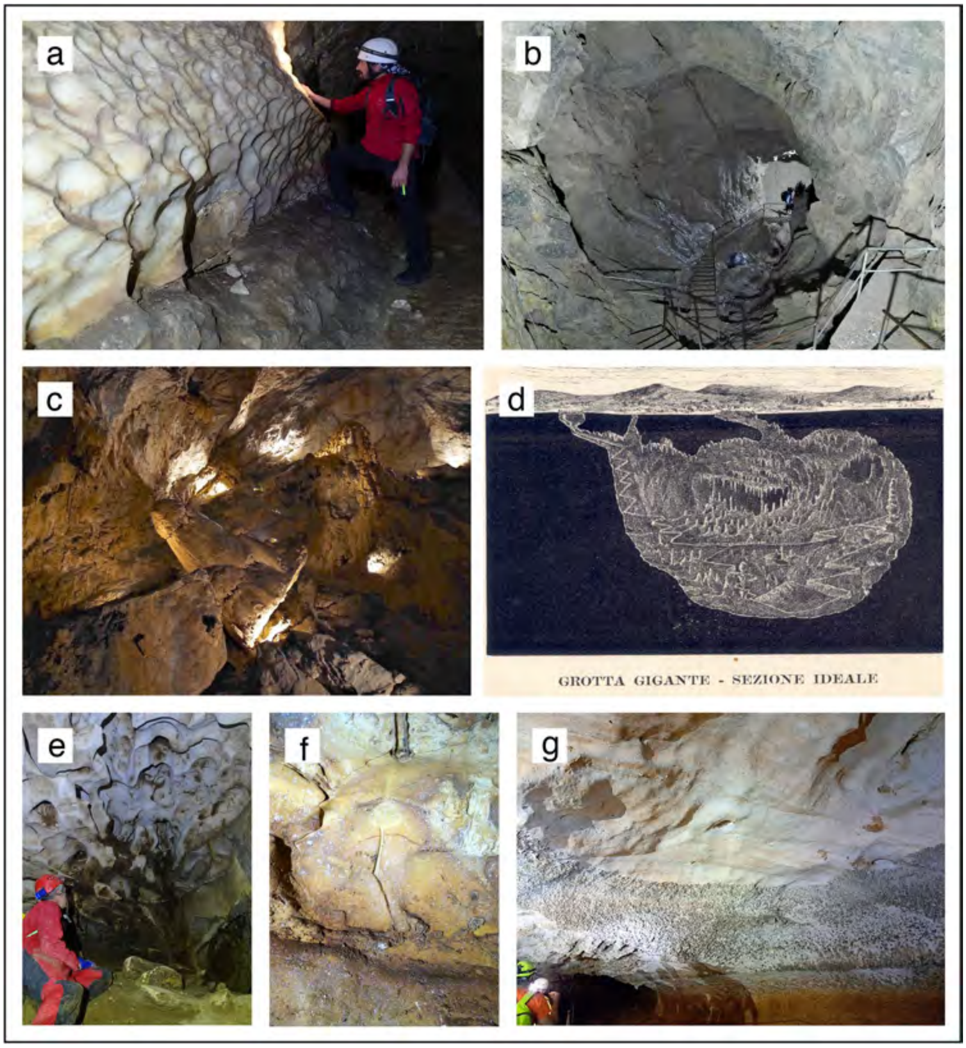

Fig. 7 Cave morphologies. **a** Scallops in the crystalline white marbles of Corchia Cave, Tuscany (photo Jo De Waele). **b** The vertical stairs going down the rounded phreatic tube in Grotta del Vento, Tuscany (photo Bartolomeo Vigna). **c** The inclined 10-m tall stalagmite in a large collapse room in Bossea Cave, Piedmont (photo Bartolomeo Vigna). **d** An old postcard showing the enormous subterranean room of Gigante Cave, near Trieste (postcard of the collection F. Anelli Library Bologna). **e** A dense network of condensation-corrosion cupolas on the roof in Castelcivita Cave, Campania (photo Jo De Waele). **f** Bubble trail in a megacusp along the walls of Castellana Cave, Apulia (photo Jo De Waele). **g** Horizontal level marked by lithophaga holes (below) and smooth walls (above) representing the MIS5e sea-level highstand in the entrance parts of Bue Marino Cave, Sardinia (photo Bartolomeo Vigna).

ages (comprised between 110 and 80 ka) with independent quartz OSL-dates and U/Th dating of two calcite flowstones above and below the sampled sand (Andreucci et al. 2017). These data show that this entrance area was open to the sandy coastline for at least the last 100 ka. The age of the cave, or at least part of the network, is far older, as Pliocene basalts filling phreatic conduits in the southern branch indicate (Mahler 1979; De Waele 2004) (Fig. 8c).

The nature of the sediments filling the highest (and thus oldest) cave levels in Monte Corchia Cave in Tuscany shows that this cave system has started forming during the Pliocene, in a geographical context that was very different from the one in which the cave appears nowadays (Piccini 2011). Speleothems in this cave have grown continuously over the last 970,000 years, as shown by the large set of U/Pb and U/Th dates on stalagmites from different areas in the cave (Isola et al. 2021).

In Bàsura Cave (Toirano, Liguria), U/Th dating and palaeomagnetic analyses have been carried out on a thick flowstone, which started forming earlier than 625 ka and stopped growing 225 ka ago (Pozzi et al. 2019). A more exact timing of speleogenesis can be obtained using the K/Ar dating method on alunite and jarosite, sulphate by-products of the weathering of clay minerals in sulphuric acid cave environments. K/Ar alunite dates (see Fig. 8d) were obtained from Cavallone Cave in Abruzzo (1.52 ± 0.28 Ma) and from Monte Cucco in Umbria (Galleria dei Barbari, 2.30 ± 0.07 Ma). All these data show that some of the largest cave systems in Italy are pre-quaternary in age.

Show caves, and their abundant speleothems, have sometimes been used to carry out palaeoclimatic studies. The presence of broken speleothems, the availability of electricity (for drilling operations), and their easy access have promoted these caves as ideal sites to perform such studies. Besides Corchia Cave in Tuscany, which is one of the most important continental palaeoclimatic reference sites in the Mediterranean (Bajo et al. 2020 and references therein), such studies were also carried out in Piedmont, at Rio Martino Cave (Regattieri et al. 2021), and in Sardinia, at Bue Marino (Columbu et al. 2017b) and at Santa Barbara Cave (Pagliara

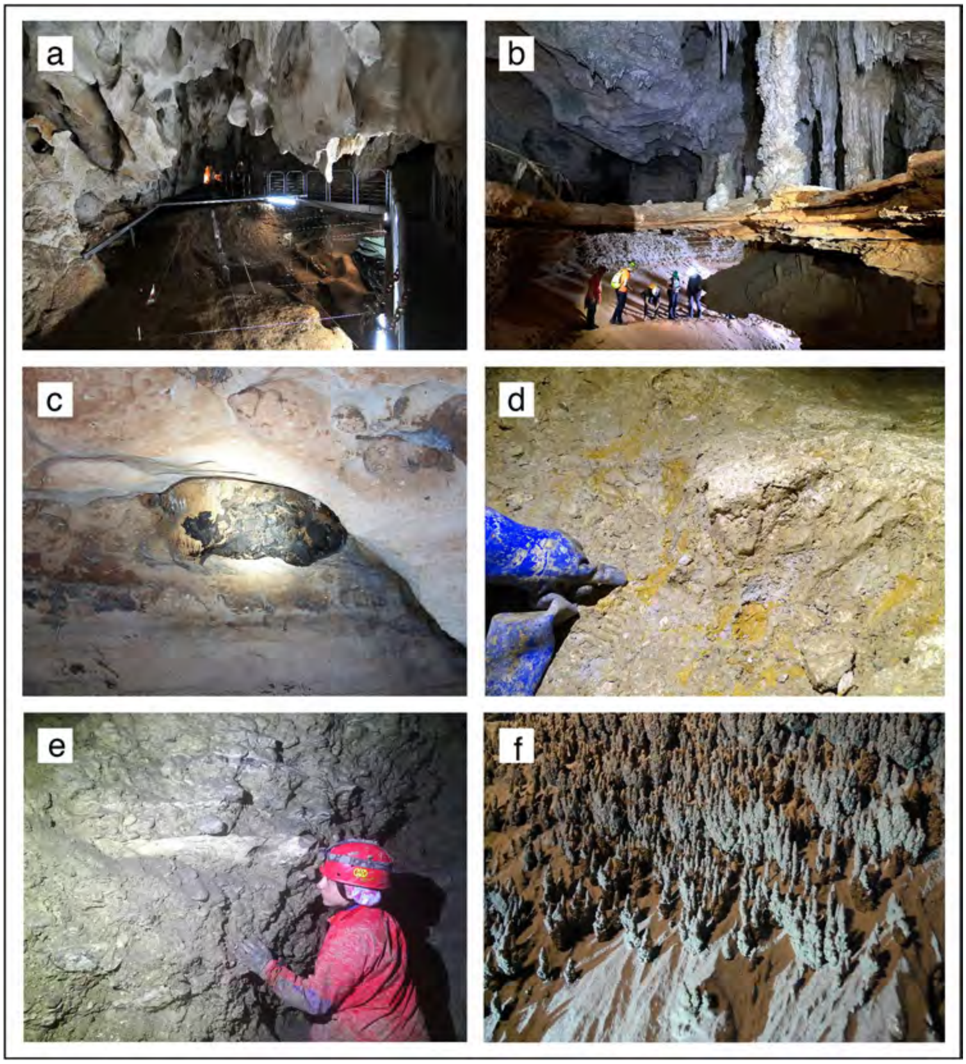

Fig. 8 Cave sediments and fillings. **a** The archaeological dig in Corbeddu Cave, central Sardinia (photo Mariantonietta Furru, Sardinia Inside). **b** Horizontally bedded windborne sand sediments in the entrance parts of Bue Marino Cave, Sardinia (photo Bartolomeo Vigna). **c** Basaltic lava flow that filled an old phreatic conduit in the southern branch of Bue Marino Cave (photo Luca Picciau). **d** Jarosite (orange) and alunite (greyish) secondary sulphuric acid weathering products in Frasassi Cave, Marche (photo Jo De Waele). **e** A fluvial sediment infilling in Re Tiberio Cave, Emilia-Romagna. Note the yellowish flowstone layer, showing cyclic clastic and chemical sedimentation (photo Jo De Waele). **f** Clay pinnacles in the sediments of Grotta del Vento, Tuscany (photo Bartolomeo Vigna)

et al. 2010). In this last system, subaqueous mammillary calcite has been dated in the lower part (Santa Barbara 2), showing these speleothems started forming before 399 ± 48 ka (the oldest date) and stopped growing around 247 ± 19 ka (Pagliara et al. 2010). Calcite speleothem ages have also been used to date speleogenetic events and to reconstruct the climate-driven control on river entrenchment and cave evolution in the gypsum areas of Emilia-Romagna (Columbu et al. 2015, 2017a). The key area for these studies was the Re Tiberio Cave (Fig. 8e).

Italian tourist caves show a considerable variety of speleothems including 90% of the forms reported in the book by Hill and Forti (1997). In Sardinia, Is Zuddas Cave hosts some of the most beautiful helictites of calcite and aragonite and a wealth of unparalleled forms (as many as 29 types of speleothems) (Fig. 9a) (Caddeo et al. 2008), whereas in Santa Barbara Cave, which was intercepted in the 1950s by mining works, visitors can observe entire walls covered with centimetre-long beige-coloured baryte crystals, grown on mammillary calcite speleothems and sometimes covered with white aragonite helictites (Fig. 9b) (Pagliara et al. 2010). In the Bàsura-Santa Lucia inferiore Cave (Toirano, Liguria), in addition to the helictites of aragonite and a vast variety of classical vadose speleothems, it is possible to observe underwater speleothems such as floating calcite, tower cones, mammillary coatings, and giant ‘poolfinger’-like speleothems, but the aerial stalactites are now covered by subaqueous calcite precipitated during submersion (Fig. 9c) (Columbu et al. 2021). In the ‘Sala Bianca’ of Castellana Cave (Apulia), and in the nearby Grotta del Trullo in Putignano, but also in some parts of Frasassi Cave (Marche) (Fig. 9d), the stalagmites are of the monocrystalline type, some with a triangular section typical of calcite crystals. In this latest cave and in Grotta Gigante (Trieste, Friuli-Venezia Giulia), it is worth mentioning the large corbelled stalagmites (Fig. 9e) that reach the beauty of the famous ones from the Aven d’Orgnac Cave in France.

In the sulphuric caves, in particular in Frasassi (Marche) and in Sant’Angelo (Cassano allo Ionio, Calabria), there are

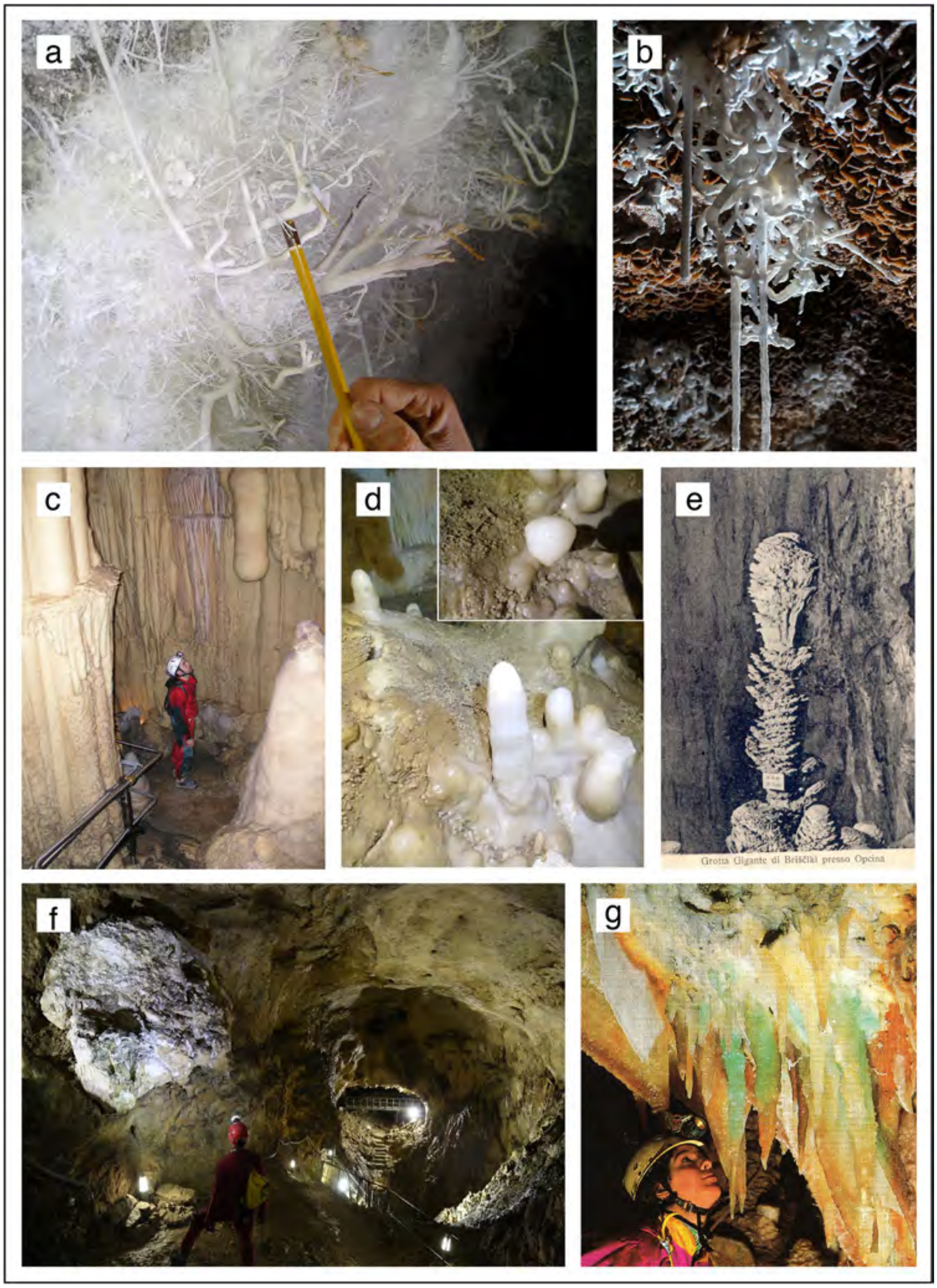

Fig. 9 Speleothems and cave minerals. **a** Aragonite helictites in Is Zuddas Cave, southwest Sardinia (photo Guglielmo Caddeo). **b** Calcite helictites grown on tabular brown baryte crystals in Santa Barbara Cave, southwest Sardinia (photo Vittorio Crobu). **c** Submerged mammillary coatings on drowned stalactites in Bàsura Cave, Liguria. Note the thickened calcite rafts on the ledge left (photo Jean-Yves Bigot). **d** Monocrystalline calcite stalagmites in Frasassi Cave, Marche. Note the triangular cross-section (inset) (photo Jo De Waele). **e**. Corbelled giant stalagmite in Gigante Cave near Trieste (old postcard of the collection F. Anelli Library Bologna). **f** Replacement gypsum (white) on the walls in the highest parts of Cavallone Cave, Abruzzo (photo Giuseppe Antonini). **g** Greenish calcite stalactites in the inner parts of Su Mannau Cave, southwest Sardinia (photo Gruppo Grotte Fluminese/Su Mannau)

large deposits of secondary white gypsum and other sulphates formed through the interaction of sulphuric acid with the surrounding rocks (D'Angeli et al. 2018; Galdenzi and Maruoka 2019). In these caves (including Monte Cucco in Umbria and Cavallone in Abruzzo, Fig. 9f)), as mentioned above, these sulphates have been used to reconstruct chronologically, and with great precision, the age of speleogenesis (D'Angeli et al. 2019a).

In the Corchia cave system (Tuscany), black crusts and nodules have revealed to be composed of phosphates mixed with minor Fe/Mn compounds. These secondary mineral deposits testify to a long-lasting mixed phreatic and air-filled precipitation of these minerals, probably driven by microbiological interactions (Piccini et al. 2021). Phosphates are often found as secondary products in caves, including many Italian show caves such as Pertosa-Auletta (Campania) and Toirano (Liguria) (Audra et al. 2019). In some caves in Sardinia, like in Su Mannau Cave, calcite speleothems can have surprising colours, including greenish (Fig. 9g) and bluish.

Speleogenesis

Cave formation (so-called speleogenesis) includes a series of processes that involve the interaction between rock, surface and underground water, and gases. Driven by carbon dioxide-rich water seeping into the carbonate massif from the surface, epigenic speleogenesis is well recognised in most of the Italian cave systems. The same cannot be said for hypogenic speleogenesis, linked to the ascent of aggressive fluids with different physico-chemical properties. Twenty-one caves (around one third) have active rivers flowing through (at least part of) them, whereas seven other caves show signs of important past fluvial activity. Thus, more than a half (ca. 56%) of Italian show caves have been carved by processes other than fluvial erosion (Table 2). Fifteen caves (23.4%) appear to have formed by the slow dissolving work of infiltrating waters. As many as seven caves were strongly influenced by the mixture of fresh and salt water in coastal areas, five are clearly the result of the mixing between deep and meteoric waters with different carbon dioxide concentrations, while four were created by sulphidic waters. Only two show the clear influence of thermal waters. One cave is mainly the result of erosion processes (by water and wind), and two are the product of the deposition of calcium carbonate and its subsequent modification (travertine). Finally, one cave represents a fine example of groundwater rising during floods. Therefore, of the 64 Italian show caves, about a quarter (28%) can be defined as hypogenic (in the sense of Palmer 2007), created by corrosion processes in which the acidity of the fluid that originated them derived mainly from non-surface sources (with little intervention of CO_2 coming directly from the surface).

The epigenic origin is straightforward, especially when active rivers still flow through the show caves. The dissolving and abrasive action of normal and flood waters on the carbonate (or gypsum) bedrock leaves, many typical morphologies including canyons, meanders, scallops, erosional notches, echinoliths (a solution feature originated by aggressive waters that create an intricate network of intersecting potholes with sharp-edged blades and rock projections), and plunge pools. However, in Bossea Cave (Piedmont), most of the void is carved in the underlying non-soluble volcanic rocks by the erosive action of the small underground river during the recurring occasional floods (Antonellini et al. 2019). In most of the fossil river caves, abundant fluvial sediments are preserved, and sometimes also cave wall morphologies are still clearly recognisable. The genesis of some caves was originally attributed to past epigenic activity based on some characteristic passage shapes, including supposedly phreatic tubes and keyhole passages. Recent investigations, however, demonstrated other processes to have dominated the various speleogenetic stages. This is the case of Toirano Cave (Liguria), the genesis of which is actually attributed mainly to mixing corrosion in a system where CO_2 rises from below, and later important phases of condensation corrosion (Columbu et al. 2021). Castellana Cave (Apulia), because of its sheer size and linearity, was generally thought to have formed by underground river erosion (Anelli 1938; Manghisi and Pace 2007), or by the prolonged dissolving action of water along some main fracture zones, the level of which was controlled by the underlying less permeable bituminous limestones (Reina and Parise 2004). The presence of spongework morphologies in certain sectors of the cave, and sets of bubble trails, on the contrary, suggest an alternative hypothesis: the cave might have formed at the interface between two bodies of slowly moving water, the infiltration water poor in CO_2, and the almost stagnant phreatic groundwater enriched in CO_2 from the underlying bituminous limestones. Ongoing isotopic investigations on cave wall rock samples will allow this interesting speleogenetic model to be resolved. Similar dissolving mechanisms might be at the origin of several other caves in Apulia (e.g. Trullo, Curtomartino, Monte Vicoli, Santa Croce), but future studies are needed to confirm these hypotheses.

Four caves are clearly related to the rising of H_2S from deep sources (so-called sulphuric acid speleogenesis or SAS caves) (D'Angeli et al. 2019b). The genesis of Frasassi Cave (Marche) has been studied since the late 1980s (Galdenzi and Jones 2017), and this incredibly interesting still active cave system has become a benchmark site for the other sulphuric acid caves in Italy (D'Angeli et al. 2019b) and worldwide. Monte Cucco Cave (Umbria) was recognised as a SAS cave soon after (Galdenzi and Menichetti 1995, 2017), and Sant'Angelo Cave (Calabria) several years later (Galdenzi 1997; Galdenzi and Maruoka 2019). The SAS origin of Cavallone Cave in Abruzzo, on the other hand, also because of its old age (over 1.5 million years), has been understood only very recently, thanks to the presence of secondary by-products (gypsum, jarosite, and alunite) and some remnants of the typical morphologies (replacement pockets, megacusps, feeders) (D'Angeli et al. 2019a).

Many caves located close to the present coastline have felt the influence of the saltwater-freshwater interface, and are thus, at least in some parts, of the flank margin cave type (Mylroie and Carew 1990). In Sardinia, the maze-like development of the parts of Bue Marino Cave closest to the present coastline, together with some typical morphologies (e.g. spongework, notches) are a clear sign of coastal mixing processes still active today. In nearby Fico Cave the flank margin origin has been demonstrated only recently (D'Angeli et al. 2015), and this cave preserves several interglacial sea-level highstands spanning the last 1 million years. Borgio Verezzi Cave in Liguria, located less than a km from the present coastline, has a labyrinthine development, shows spongework morphologies, and contains old flowstones corroded by mixing solutions. This cave surely is related to saltwater-freshwater mixing, probably during more than one interglacial cycle. Of course, both Grotta Azzurra and Grotta dello Smeraldo in Campania are at least partly influenced by coastal mixing corrosion, and so are Zinzulusa (Apulia) and Nettuno (Sardinia) caves, with spongework morphologies, mixing notches, and a more or less complicated maze pattern. Most of these caves are carved in telogenetic limestones, and saltwater-freshwater mixing mainly occurred along preferential pathways (e.g. fractures with freshwater flow).

Only two caves are of clear thermal origin: Maona Cave (Tuscany) has smooth morphologies, is clearly oriented along some major fractures, and is related to nearby active thermal springs (Panichi et al. 2016). Santa Barbara Cave (Sardinia), on the contrary, is a single room, entirely covered with subaqueous mammillary calcite deposits on which thermal centimetre-scale baryte crystals have grown. The cave is probably related to the action of rising fluids during the Oligo-Miocene volcanic period that characterised SW Sardinia (Pagliara et al. 2010). Finally, two cave areas are composed of travertine hollows, related to Quaternary deposition of calcareous tufa. In the Belverde area (Tuscany), the trail crosses a series of more or less small caves, the longest of which reaches over 300 m in length, most of which have archaeological interest. Rescia Cave (Lombardy), on the other hand, is composed of a few travertine caves connected by artificial tunnels.

Conclusions

The geodiversity richness of show caves is not easy to assess and recognise, especially by the general public that is generally less prone to attribute a natural value to non-living elements. The long geological history of Italy and its current geodynamics have determined the extraordinary variety of underground environments according to the different lithologies in which they develop (limestones, dolostones, conglomerates in calcareous flysch, marbles, gypsum, and travertines), to the speleogenetic processes that contributed to their formation, and to the richness in speleothems and secondary mineralizations they preserve. The presence of show caves has been the driving force for studying the fragility of caves and the sustainability of cave tourism, increasing the scientific and multidisciplinary knowledge on Italian karst areas over the last decades. The Italian show caves represent an enormous historical and natural heritage, able to introduce a large public to the scientific wonders of the underground world, creating opportunities for their conservation and, at the same time, developing economic and social well-being for the communities involved. Show caves, when properly managed, ensure cultural growth for the generations of onlookers who have visited, and will continue to visit, the spectacular world of caves.

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